Intrapulmonary shunt after cardiopulmonary bypass: The use of vital capacity maneuvers versus off-pump coronary artery bypass grafting

Edda M. Tschernko, MD[a]
Anton Bambazek, MD[a]
Wilfried Wisser, MD[b]
Bernhard Partik, MD[b]
Ursula Jantsch, MD[a]
Klaus Kubin, MD[b]
Marek Ehrlich, MD[b]
Walter Klimscha, MD[a]
Michael Grimm, MD[b]
Franz P. Keznickl, MD[a]

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Objectives: It has been proved in human subjects and animals that atelectasis is a major cause of intrapulmonary shunting and hypoxemia after cardiopulmonary bypass. Animal studies suggest that shunting can be prevented entirely by a total vital capacity maneuver performed before termination of bypass. This study aimed to test this theory in human subjects and to evaluate possible advantages of off-pump coronary artery bypass grafting.

Methods: Twenty-four patients scheduled for coronary artery bypass grafting were randomly assigned to receive no total vital capacity maneuver (control group, n = 12) or standard total vital capacity maneuvers (TVCM group, n = 12). Additionally, 12 consecutive patients undergoing off-pump coronary artery bypass grafting (off-pump group) were studied. Systemic and central hemodynamics, the pattern of breathing, and ventilatory mechanics were evaluated after induction of anesthesia, after sternotomy, after cardiopulmonary bypass and skin closure, and 4 hours after extubation.

Results: The use of total vital capacity maneuvers reduced ($P < .05$) intrapulmonary shunting after termination of cardiopulmonary bypass. However, shunting increased ($P < .05$) in all groups (control group, 8.2% ± 3.3% vs 25.6% ± 8.1%; TVCM group, 8.7% ± 3.4% vs 24.4% ± 8.5%; and off-pump group, 7.8% ± 2.8% vs 14.0% ± 5.3%) after extubation, but the increase was significantly ($P < .05$) less pronounced in the off-pump group. Furthermore, pulmonary compliance decreased ($P < .05$) in all groups except the off-pump group after extubation. Duration of hospital and intensive care unit stay was significantly shorter ($P < .05$) in the off-pump group than in the other groups.

Conclusion: The development of intrapulmonary shunting and hypoxemia after coronary artery bypass grafting can be substantially reduced by performance of total vital capacity maneuvers while patients are mechanically ventilated. However, off-pump coronary artery bypass surgery is superior in preventing shunting and hypoxemia after bypass grafting in the immediate and early postoperative periods, probably leading to substantially shorter intensive care unit and hospital stays.

From the Departments of Cardiothoracic Anesthesia and CCM[a] and Clinical Pharmacology and the Department of Cardiothoracic Surgery,[b] University of Vienna, General Hospital, Vienna, Austria.

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Address for reprints: Edda M. Tschernko, MD, Associate Professor of Cardiothoracic Anesthesia and CCM, Department of Cardiothoracic Anesthesia and CCM, University of Vienna, Vienna General Hospital, Waehringer Guertel 18-20, A-1090 Vienna, Austria (E-mail: edda.tschernko@univie.ac.at).

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Impairment of pulmonary gas exchange is well documented after cardiopulmonary bypass (CPB) for cardiac operations.[1] In 1994, Hachenberg and colleagues[2] showed, in 9 patients, that intrapulmonary shunt (Qs/Qt) caused by atelectasis formation is a major component of impaired gas exchange after cardiac operations performed with CPB.[2] The use of CPB was identified as the major cause of atelectasis formation in an experimental study by Magnusson and coworkers.[3] However, postoperative atelectasis formation and intrapulmonary shunting could be completely prevented in the experimental animals by performing a standardized total vital capacity maneuver (TVCM) before termination of CPB.[4] This clinically relevant finding has, to the best of our knowledge, not been tested in human subjects. Furthermore, little is known about the effect of CPB on intrapulmonary shunting and oxygenation after termination of mechanical ventilation. The existing data indicate that ventilatory strategies do not influence oxygenation after termination of mechanical ventilation in the early postoperative period.[5] Therefore it was the aim of this prospective, randomized, open-label study to answer the following questions: (1) Is the use of CPB the predominant cause for intrapulmonary shunting after coronary artery bypass grafting (CABG) in human subjects and can it be prevented with off-pump coronary artery bypass grafting (OPCAB)? (2) Does the use of CPB still influence intrapulmonary shunting and oxygenation after termination of mechanical ventilation ? (3) Can standardized TVCMs performed before termination of CPB completely prevent intrapulmonary shunting after CABG?

Materials and Methods

Study Population and Group Assignment

The study was approved by the Institutional Review Board of the Vienna University Medical Center. Written informed consent was obtained from 36 patients scheduled for CABG. Inclusion criteria for the study were as follows: (1) stable angina pectoris caused by coronary artery disease; (2) left ventricular ejection fraction of greater than 40%; (3) absence of significant preoperative lung malfunction, as determined by means of clinical examination, chest radiography, lung function testing (forced vital capacity >80% of the predicted value and forced expiratory volume in 1 second >80% of the predicted value), and blood gas analysis; and (4) absence of coexisting renal, hepatic, or cerebrovascular disease or insulin-dependent diabetes mellitus.

Twelve of the 36 patients were assigned by the cardiac surgeon to undergo OPCAB (off-pump group). By using a computer-generated random-number table, the remaining 24 patients were randomly allocated to one of 2 groups. Patients assigned to the control group (n = 12) were ventilated with an inspiratory time/expiratory time ratio of 1:2 before and after CPB, and no TVCM was performed. Patients assigned to the TVCM group (n = 12) were ventilated as for control patients, except that 3 TVCMs were performed immediately before termination of CPB. Patients undergoing OPCAB surgery (off-pump group, n = 12) were ventilated as for control patients throughout the entire surgical procedure. Groups were comparable in respect to age and body mass index (Table 1).

TABLE 1. Demographic data and preoperative pulmonary function test parameters

	Control group	TVCM group	Off-pump group
Age (y)	64 ± 11	67 ± 11	64 ± 6
Body weight (kg)	80 ± 14	81 ± 11	74 ± 8
Height (cm)	175 ± 12	173 ± 9	171 ± 8
BMI (kg/m^2)	26.6 ± 2.8	27.2 ± 3.0	25.4 ± 1.8
FVC (%)	100 ± 12	93 ± 6	95 ± 4
FEV_1 (%)	94 ± 13	94 ± 8	98 ± 11
$Pa{O_2}$ (mm Hg)	77 ± 9	80 ± 8	78 ± 11

Presented are preoperative values (mean ± SD) determined within 1 month before the operation. None of the parameters showed a significant difference between groups. *FVC*, Forced vital capacity; *FEV_1*, forced expiratory volume in 1 second.

Anesthesia, Mechanical Ventilation, and TVCM

Baseline measurements of arterial blood gases, pattern of breathing, and ventilatory mechanics were performed in a half-sitting position immediately before induction of general anesthesia. Patients did not receive premedication to avoid the effect of sedation on the preanesthesia measurements. Anesthetic management was standardized.

After tracheal intubation, the lungs were ventilated with intermittent positive pressure ventilation (Cicero; Draeger, Luebeck, Germany) by using 40% oxygen in air, a tidal volume (V_T) of 10 mL · kg^{-1}, a respiratory frequency (RF) keeping $Pa{CO_2}$ in the normal range (±3 mm Hg from the preoperative value), and a positive end-expiratory pressure (PEEP) of 5 cm H_2O. This respirator setting (fraction of inspired oxygen, V_T, RF, and PEEP) was maintained before and after CPB and only changed if a drop in arterial oxygen saturation ($Sa{O_2}$) to less than 90% occurred. In this case data were not used for further analysis (drop out). Four patients from the control group experienced an $Sa{O_2}$ of less than 90% after termination of CPB. The respirator setting had to be changed in these patients, and TVCMs were performed. The data for these patients were not used for further analysis. The respirator setting could be maintained in the remaining 32 patients.

In patients assigned to the TVCM group, a TVCM was performed by inflating the lungs to 40 cm H_2O and holding this pressure for 15 seconds immediately before termination of CPB.[4] This TVCM was repeated 3 times. Control patients and off-pump patients were not treated with a TVCM. In the intensive care unit (ICU), all patients were weaned from mechanical ventilation by using airway pressure-release ventilation-biphasic positive airway pressure, a pressure-controlled mode (Evita 4; Draeger, Luebeck, Germany). Inspired oxygen concentration was maintained at 40%, and PEEP was maintained at 5 cm H_2O until termination of mechanical ventilation. Patients were successfully separated from mechanical ventilation, and the trachea were extubated 4 to 15 hours postoperatively. Postextubation measurements were then undertaken 4 hours after extubation.

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Cardiopulmonary Bypass

A median sternotomy was performed in all 36 patients. In the 24 patients undergoing CABG with bypass, heparin sodium (300 IU $\cdot$ kg^{-1}) was administered, and the activated clotting time was kept at greater than 400 seconds (Hemochrom 400; International Technidyne Corp, Edison, NJ). The extracorporal circuit consisted of a membrane oxygenator (Monolyth, Sorin Biomedica Cardio, Saluggia, Italy), an open venous reservoir system (Monolyth, Sorin Biomedica Cardio), and polyvinyl chloride tubing. Ringer lactate solution (1700 mL), mannitol 20% (100 mL), and heparin sodium (5000 IU) were used to prime the circuit. During extracorporal circulation, body core temperature was maintained at 36°C (normothermic CPB). Cardioplegic cardiac arrest was achieved with cold (4°C) induction (blood cardioplegic solution; Buckberg, Dr Köhler Pharma GmbH, Vienna, Austria). During aortic cross-clamping cold cardioplegic solution was reinfused through the coronary sinus in 20-minute intervals. Mechanical ventilation was terminated after cardioplegic cardiac arrest, and the airway was left exposed to air. In the 12 patients undergoing OPCAB surgery (off-pump group), heparin sodium (100 IU $\cdot$ kg^{-1}) was administered, and mechanical ventilation was performed as described above throughout the entire procedure. A CTS stabilizer (Cardio Thoracic Systems, GUIDANT, Cupertino, Calif) was used for stabilization of the operative area. The heparin effect was reversed in all patients with protamine (1 mg for each 100 IU used).

Measurements and Study Protocol

Hemodynamic measurements. Before induction of anesthesia, a 20-gauge catheter was introduced into the left or right radial artery for pressure measurements and blood sampling. After induction of general anesthesia, a triple-lumen, thermistor-tipped, 7.5F pulmonary artery catheter was transcutaneously introduced through the right internal jugular vein into a pulmonary arterial wedge position. Pulmonary artery pressure, central venous pressure (CVP), and pulmonary capillary wedge pressure (PCWP) were measured. $Pa{O_2}$, $Pa{CO_2}$, $PV{O_2}$ (mixed venous oxygen partial pressure), and $PV{CO_2}$ (mixed venous carbon dioxide partial pressure) were determined by means of standard techniques (ABL 750; Radiometer, Copenhagen, Denmark). Cardiac output was measured by means of standard thermodilution (Explorer; Baxter Healthcare Corporation, Irvine, Calif). Derived data, such as cardiac index (CI), systemic vascular resistance index (SVRI), and pulmonary vascular resistance index, were calculated with standard formulas. The alveolar-arterial oxygen gradient (P_A-aO_2) was calculated from the alveolar gas equation. Measurements were undertaken 20 minutes after insertion of the pulmonary artery catheter (before skin incision), 10 minutes after sternotomy, 20 minutes after termination of CPB (sternum open), 30 minutes after closure of the sternum, and 4 hours after tracheal extubation. Surgical intervention was held during measurements.

Ventilatory measurements. Baseline measurements of ventilatory mechanics and the pattern of breathing were performed in a half-sitting position in the awake, spontaneously breathing patients before induction of anesthesia. After local anesthesia of the nasopharynx with lidocaine 2% spray, an esophageal balloon catheter was inserted through the nose into the esophagus for measurements of ventilatory mechanics. Thereafter, a resting period of 10 minutes was allowed before baseline measurements of ventilatory mechanics and assessment of arterial blood gas values.

For assessment of ventilatory mechanics in spontaneously breathing patients (preoperative and after extubation), airflow was measured with a flow sensor (Varflex, Bicore CP-100 monitor; Bicore Monitoring Systems Inc, Irvine, Calif) connected to a tightly adjusted face mask.[6] The fit of the face mask was evaluated by comparing inspiratory and expiratory volumes. A difference of less than 5% was regarded as sufficiently tight. V_T was obtained by integration of the flow signal. Airway pressure (P_{aw}) was measured through a catheter attached to the flow sensor, and esophageal pressure (P_{es}) was measured with a 7F nasogastric tube (Varflex, Bicore Monitoring Systems Inc) incorporating an esophageal balloon (noncompliant polyethylene, 0.8-mL filling volume). The correct position of the balloon catheter was verified by using the occlusion test.[7] The esophageal balloon and the flow sensor were connected to a portable monitor (CP-100 cardiopulmonary monitor, Bicore Monitoring Systems Inc) that provided a real-time display of airflow, volume, P_{aw}, and P_{es} tracings. Loops of P_{es} versus airflow and P_{aw} versus airflow relationships were derived from this device.[8]

Minute ventilation and breathing pattern (ie, V_T, RF, and duration of inspiration and expiration) were analyzed from the flow signal. Total resistive work of breathing values were obtained by integrating the area subtended by P_{es} and lung volume during a complete respiratory cycle. Pulmonary resistance (R_L) was calculated by dividing transpulmonary pressure by the difference of inspiratory and expiratory airflow. Compliance was calculated as V_T divided by the end-inspiratory pressure minus the end-expiratory pressure. The pattern of breathing, work of breathing, pulmonary compliance, and R_L were calculated from 39 breaths, after excluding values that differed from the mean by more than 2 SDs. The excluded values are most likely artifacts caused by swallowing.

Pain and sedation measurements. A 100-mm linear visual analogue scale score was used for pain assessment, with 0 mm corresponding to no pain and 100 mm corresponding to the worst imaginable pain after the operation. Additionally, a sedation score ranging from 0 to 4 was determined before postextubation measurements: 0, patient communicates with attending person without being addressed; 1, patient is asleep but answers when addressed by name; 2, patient awakens when touched; 3, patient shows no reaction when touched and addressed by name loudly but responds to pain stimuli; and 4, patient does not react to pain stimuli.

Postoperative Treatment

After extubation, mask continuous positive airway pressure (CPAP) was used for treatment of atelectasis if diagnosed by means of a chest radiograph and accompanied by an $Sa{O_2}$ of less than 92% during oxygen breathing (3 L/min) through nasal prongs. During mask CPAP, end-expiratory pressure was maintained at 10 cm H_2O for at least 20 minutes while breathing 40% oxygen in air.

Statistical Analysis

Data are presented as means $\pm$ SD if not otherwise stipulated. The comparison between preoperative and postoperative values within the same group was performed with the paired Student *t* test after testing for normal distribution of the data. Comparison of changes

TABLE 2. Treatment data

Group	Control group	TVCM	Off-pump group
CABG (n)	2.9 ± 0.6	2.8 ± 0.7	2.6 ± 0.7
Surgical time (min)	284 ± 55	276 ± 57	241 ± 32
ECC (min)	89 ± 18	98 ± 35	—
ACC (min)	56 ± 19	56 ± 15	—
Mechanical ventilation (min)	978 ± 278	1151 ± 416	873 ± 404
Fluid balance (mL · kg^{-1} · min^{-1})	0.1 ± 0.02	0.1 ± 0.03	0.11 ± 0.03
VAS (mm)	38 ± 15	36 ± 18	39 ± 18
Sedation score	1.4 ± 0.5	1.6 ± 0.5	1.5 ± 0.5
Vasoactive drugs (No. of patients)	2/8	3/12	3/12

Norepinephrine or epinephrine were used as vasoactive drugs, and the maximum dose was 0.1 $\mu g \cdot kg^{-1} \cdot min^{-1}$. *ECC*, Extracorporal circulation; *ACC*, aortic crossclamping; fluid balance, positive fluid balance from the start of anesthesia to postoperative measurements (after extubation) in relation to body weight and time.

in examined parameters between groups was performed with 2-way analysis of variance.

Results

Baseline

Groups were comparable in respect to demographic and lung function data (Table 1). Additionally, systemic and central hemodynamic parameters, ventilatory mechanics, and the pattern of breathing were comparable between groups at baseline. Other treatment data, such as duration of CPB and aortic crossclamping, fluid balance, and postoperative pain and sedation score, were comparable and are shown in Table 2.

Systemic and Central Hemodynamics

Parameters characterizing systemic and central hemodynamics are presented in Table 3. The shown parameters were evaluated after induction of anesthesia (baseline) and after skin closure (postoperative). No gross hemodynamic abnormalities were observed before and during the operation or during the postoperative course in our entire patient population. Heart rate increased ($P < .05$) in all groups after the operation. CI increased ($P < .05$) in all groups except the off-pump group ($P > .05$). Systemic vascular resistance decreased ($P < .05$) in all groups except the off-pump group ($P > .05$), whereas mean arterial pressure and PCWP remained unchanged ($P > .05$) in all groups. Mean pulmonary artery pressure, pulmonary vascular resistance index, and CVP remained unchanged ($P > .05$).

Gas Exchange

Four hours after extubation, the off-pump group showed significantly ($P < .05$) higher Pa_{O_2} values (67.8 ± 8.2 mm Hg) compared with those of the other groups (control group, 60.6 ± 6.3 mm Hg; TVCM group, 59.4 ± 6.7 mm Hg). Additionally, the off-pump group exhibited significantly ($P < .05$) higher Pa_{O_2} values compared with those of the other groups before extubation. However, the control group exhibited lower ($P < .05$) Pa_{O_2} values (116.2 ± 42.1 mm Hg) after termination of CPB compared with those of the other groups (TVCM group, 197.7 ± 60.5 mm Hg; off-pump group, 219.9 ± 45.8 mm Hg).

Qs/Qt was higher ($P < .05$) in the control group (16.8% ± 6.7%) compared with values in the other groups (TVCM group, 10.7% ± 4.3%; off-pump group, 6.9% ± 2.8%) after termination of CPB (Figure 1). Additionally, the off-pump group showed less ($P < .05$) Qs/Qt (14.0% ± 5.3%) after extubation compared with that seen in all other groups (control group, 25.6% ± 8.1%; TVCM group, 24.4% ± 8.5%). No difference in Qs/Qt was found between the control and TVCM groups after surgical intervention during spontaneous breathing of room air.

The P_A-a_{O_2} was higher ($P < .05$) in the control group compared with that seen in the off-pump group after CPB and after the operation (Table 3). After extubation, P_A-a_{O_2} was lower in the off-pump group compared with that seen in the other groups.

Ventilatory Mechanics and Pattern of Breathing

The main parameters representing ventilatory mechanics and the pattern of breathing are shown in Table 4. V_T was significantly ($P < .05$) reduced after extubation compared with preoperative, awake, resting breathing in all groups except the off-pump group, whereas RF remained unchanged after extubation. Mean R_L was significantly ($P < .05$) increased in the control group compared with that seen in the preoperative state, whereas R_L remained unchanged in all other groups. Dynamic pulmonary compliance was reduced ($P < .01$) in all groups except the off-pump group after extubation when compared with the preoperative value determined during spontaneous breathing. Absolute dynamic pulmonary compliance was higher ($P < .05$) in the off-pump group compared with that seen in all other groups after extubation.

Sedation and Pain Scores after Extubation

Sedation and pain scores were comparable among groups after the operation (Table 2).

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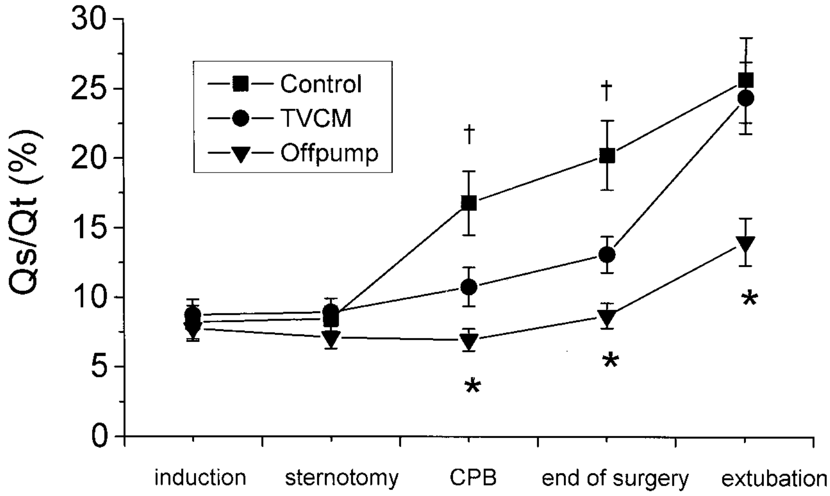

Figure 1. Qs/Qt in percentage is shown at different measuring time points (x axis). *Asterisks* indicate a significant difference of the off-pump group compared with values of all other groups, and *daggers* indicate a significant difference of the control group compared with values of all other groups. Data are means ± SEM.

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TABLE 3. Hemodynamics

	Control group		TVCM group		Off-pump group	
	Baseline	Postoperative	Baseline	Postoperative	Baseline	Postoperative
HR (beats/min)	49.4 ± 6.6	81.9 ± 15.9*	49.3 ± 8.1	77.4 ± 10.6*	57.1 ± 9.8	72.2 ± 13.1*
MAP (mm Hg)	75.4 ± 10.0	77.0 ± 7.8	85.0 ± 9.4	81.8 ± 10.3	82.9 ± 16.0	77.9 ± 12.7
MPAP (mm Hg)	22.6 ± 4.8	25.6 ± 4.8	21.7 ± 5.6	23.8 ± 3.6	23.4 ± 6.7	21.8 ± 4.6
CVP (mm Hg)	13.7 ± 2.4	15.8 ± 2.3	12.5 ± 3.3	14.9 ± 1.8*	12.9 ± 3.6	14.5 ± 4.6
PCWP (mm Hg)	14.3 ± 2.7	15.6 ± 3.2	13.6 ± 4.1	14.2 ± 2.4	13.5 ± 3.8	13.8 ± 3.3
CI ($L \cdot min^{-1} \cdot m^{-2}$)	1.7 ± 0.4	2.2 ± 0.4*	1.9 ± 0.3	2.5 ± 0.6*	1.9 ± 0.3	2.2 ± 0.7
SVR	2949 ± 664	2116 ± 353*	3135 ± 639	2334 ± 499*	2971 ± 849	2860 ± 425
PVR	355 ± 113	335 ± 123	328 ± 210	330 ± 88	335 ± 58	313 ± 98
P_A-ao_2	153 ± 40	211 ± 35*	138 ± 35	177 ± 46*	129 ± 42	128 ± 46†

Hemodynamic values determined after induction of anesthesia are shown in comparison with hemodynamic values determined within 30 minutes after the operation. *HR*, Heart rate; *MAP*, mean arterial pressure; *MPAP*, mean pulmonary artery pressure; *CVP*, central venous pressure; *SVR*, systemic vascular resistance; *PVR*, pulmonary vascular resistance.

*$P < .05$ compared with the baseline state; †$P < .01$ compared with the control group.

Clinical Outcome Data

The duration of hospital stay was significantly shorter in the off-pump group (7.5 ± 0.8 days) compared with that in the control group (12.6 ± 2.3 days, $P < .001$) and the TVCM group (10.3 ± 2.2 days, $P < .01$). Furthermore, the duration of hospital stay was shorter ($P < .05$) in the TVCM group compared with that in the control group. The duration of ICU stay was significantly shorter in the off-pump group (18.7 ± 5.4 hours) compared with that in the control group (69.6 ± 60.0 hours, $P < .03$) and the TVCM group (28.8 ± 9.6 hours, $P < .03$). The duration of ICU stay showed a tendency to be shorter ($P = .07$) in the TVCM group compared with that in the control group. One of the patients of the control group had postoperative lobar pneumonia, requiring an ICU stay of 9 days. Another patient of the control group had severe recurrent atelectasis accompanied by hypoxemia, requiring an ICU stay of 4 days. None of the patients of the TVCM group required an ICU stay of longer than 2 days, and none of the patients of the off-pump group required an ICU stay of longer than 1 day.

For the treatment of postoperative atelectasis accompanied by hypoxemia, mask CPAP had to be used in 7 of 8 patients of the control group, in 6 of 12 patients of the TVCM group, and in 3 of 12 patients of the off-pump group.

Discussion

The main finding of the present study is a significant reduction in Qs/Qt during surgical intervention and after extubation in patients undergoing OPCAB surgery. This reduction in shunting was associated with improved intraoperative

TABLE 4. Ventilatory parameters

	Control group		TVCM group		Off-pump group	
	Baseline	Postoperative	Baseline	Postoperative	Baseline	Postoperative
V_T (L)	0.65 ± 0.31	0.42 ± 0.20*	0.50 ± 0.17	0.43 ± 0.11*	0.50 ± 0.10	0.44 ± 0.13
RF (breath $s \cdot min^{-1}$)	14.3 ± 4.9	16.5 ± 4.4	15.4 ± 5.5	15.9 ± 4.3	13.6 ± 5.2	14.7 ± 4.8
Resistance (cm $H_2O \cdot L^{-1} \cdot s^{-1}$)	8.3 ± 4.3	12.4 ± 4.4*	9.8 ± 4.1	9.9 ± 4.8	13.4 ± 10.7	12.5 ± 5.3
Compliance (mL $\cdot$ cm H_2O^{-1})	130 ± 58	64 ± 27*	112 ± 38	61 ± 15*	114 ± 33	137 ± 80†

*$P < .05$ compared with preoperative value; †$P < .05$ compared with control group.

and postoperative oxygenation associated with reduced duration of ICU stay and hospital stay. However, the performance of TVCMs significantly reduced shunting after termination of CPB but could not completely abolish shunting and hypoxemia after extracorporal circulation. Furthermore, the performance of TVCMs could not reduce intrapulmonary shunting and hypoxemia after extubation.

Systemic and Central Hemodynamics

The findings of increased heart rate and CI, as well as decreased SVRI, in patients undergoing CABG with extracorporal circulation are comparable with the findings of Hachenberg and associates[9] and Berry and coworkers (Table 3).[10] However, CI did not increase in the off-pump group, probably because of unchanged SVRI (Table 3). Because there was no difference in the use of vasoactive drugs between groups (Table 2), it is likely that the use of the extracorporal circuit is associated with decreased SVRI, leading, together with increased heart rate, to increased CI. However, this increase in blood flow probably has little effect on pulmonary blood volume in normal lungs.[9,11] Thus it is unlikely that impaired lung function can be attributed to increased CI.

An increase in PCWP is associated with increased lung water, leading to impairment of oxygenation,[12,13] and is thus one possible factor contributing to postoperative impairment in gas exchange. However, PCWP was unchanged in our patients after surgical intervention (Table 3). Therefore changes in PCWP do not seem to be responsible for impaired oxygenation. Nevertheless, we cannot comment on changes in lung water because we did not measure this parameter. In summary, differences in hemodynamics do not seem responsible for increased intrapulmonary shunting in our patients.

Gas Exchange

Increased Qs/Qt is a well-documented and undesirable phenomenon after separation from CPB.[2-4] This effect is especially pronounced if the lungs are not inflated to total lung capacity immediately before termination of CPB. This effect of pulmonary atelectasis during CPB on post-CPB oxygenation and shunting could be clearly demonstrated in the control group (Figure 1). Magnusson and associates[4] found no increase in intrapulmonary shunting after CPB in pigs ventilated with 40% fraction of inspired oxygen if a TVCM was performed before termination of CPB. In contrast, we found increased ($P < .05$) Qs/Qt in all groups except the off-pump group after surgical intervention when compared with Qs/Qt after induction of anesthesia (Figure 1). The 2 main differences between the study of Magnusson and associates and our study were that (1) CABG was performed in our patients, whereas the experimental animals underwent CPB but did not undergo CABG, and (2) we performed measurements in human subjects. Thus it seems possible that mechanical trauma of the lungs during CABG might play a role in the development of postoperative intrapulmonary shunting and hypoxemia in patients. To what extent differences between human and animal lung structure can influence the results remains unclear.

The effect of the treatment with TVCMs on oxygenation and on Qs/Qt (Figure 1) was not sustained after extubation. Differences in the degree of postoperative sedation and pain score are not responsible for this observation (Table 2). An increase in Qs/Qt could also be observed in the off-pump group after extubation; however, Qs/Qt remained substantially lower compared with that seen in the other groups. Therefore it can be concluded that the use of extracorporal circulation is very likely responsible for a significant amount of Qs/Qt in patients undergoing CABG during the postoperative period after extubation. This finding is in line with the finding of Guler and colleagues[14] that atelectasis formation after CABG occurs less often in patients operated on with an off-pump technique. Similar to Guler and colleagues, we found reduced duration in the average ICU stay in the off-pump group. Therefore it seems likely that reduced Qs/Qt associated with improved oxygenation before and after extubation beneficially influenced these clinical parameters in the off-pump group. However, duration of hospital stay was also shorter in patients treated with TVCMs compared with in control patients. The sole difference in treatment between the 2 patient populations was the performance of TVCMs, leading to a transient reduction in shunting and improvement in oxygenation. Thus it seems likely that even a transient reduction in Qs/Qt by means of TVCMs can beneficially influence the postoperative course after CABG.

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Ventilatory Mechanics and Pattern of Breathing

Acute restrictive pulmonary deficits are well-documented sequels of cardiac surgery.[15] Similar to other authors, we observed decreased V_T in patients undergoing CABG with CPB (Table 4).[16] In contrast, V_T remained unchanged in the off-pump group. Because surgical incision, sedation score, and pain score were comparable (Table 2), none of these treatment parameters can be responsible for this observation. Pulmonary compliance decreased in all groups except the off-pump group (Table 4). This might be at least partially responsible for unaltered V_T in the off-pump group. Therefore an obvious advantage of avoiding the extracorporal circuit is unchanged pulmonary compliance after extubation. Additionally, unchanged V_T after OPCAB surgery is likely preventive against formation of atelectasis, with a consequent increase in Qs/Qt and an associated decrease in $Pa{O_2}$. After extubation, mask CPAP was more often required in the control group and the TVCM group compared with in the off-pump group. This might be partially due to unchanged V_T after OBCAB surgery. Furthermore, this is well in line with our findings of decreased Qs/Qt and increased $Pa{O_2}$ in patients treated with OPCAB compared with that seen in patients undergoing CABG with the use of CPB.

In summary, our findings suggest that the avoidance of CPB is beneficial because intrapulmonary shunting and associated undesirable impairment of oxygenation during the postoperative period can be substantially ameliorated with OPCAB surgery in patients undergoing CABG with no significant preoperative impairment of lung function. Reduced shunting, improved oxygenation, and unchanged V_T seem to be at least partially responsible for reduced duration of ICU stay and hospital stay observed in the off-pump group. In patients with preoperative pulmonary impairment, this effect might be even more pronounced. If CPB is necessary for CABG, ventilatory treatment with TVCMs can effectively ameliorate impairment in oxygenation after termination from CPB but is not effective beyond extubation.

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